

## **Pressure-Tolerant Batteries for Autonomous Undersea Applications**

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### **LONG-TERM GOALS**

High performance power sources constitute a critical technology for our core business -- developing and building autonomous underwater vehicles. As these vehicles reach new levels of autonomy and reliability, and as their areas of application expand, the demand for improved energy supply grows continually. Using emerging Advanced Lithium Battery technology, Bluefin set out to advance the state of the art in subsea energy storage in the following areas: (a) Energy density with respect to weight and volume, including all housings, cabling, and support electronics and at temperatures typical of the sub sea environment; (b) Safety , user friendliness, and robustness in handling, operation, storage and shipping, charging (c) AUV design freedom and scalability to high energy requirements, no restrictions on vehicle attitude in operation etc.; (d) Ultimate life and life time cost of batteries. Our goal was to build a practical, high performance battery at a reasonable level of technical risk, for use in our own vehicles, as well as for sale to other subsea industries. The longer term goals include expanding into other markets, as well as continual technical advances that exploit the expected improvements in price, performance and safety of these cells. Consumer applications for these cells will drive availability up, price down, and performance ever closer to the theoretical limits in the years ahead.

### **OBJECTIVES**

The technological objectives of our effort can be broken down as follows:

*Electrical* The first phase involved setting specifications for cells, selecting candidate cells, and putting them through a testing schedule to be confident they would perform under isostatic pressure. We needed to establish a close relationship with the cell supplier. Deciding on the battery architecture was another early objective, identifying the best way of connecting the cells in series and parallel for the voltage we required, while minimizing inter-cell connections and wiring to the load/charger. Wet

wiring was based on standard connectors, and a requirement that a flooded connector should not cause a short.

*Intelligence* It was clear from the start that the battery would need a set of electronics with embedded firmware to handle all the functions relating to battery protection, fault management, communication, enabling, and conditioning. We set out to design this from the start. After 5 board revisions we have a robust and full-fledged set of capabilities. Building prototypes and performing tests was required to determine cell balancing requirements and develop a practical interface. Identification of and protection against battery failure modes was another important objective.

*MECHANICAL* The mechanical objectives included finding the optimal assembly method for cells, developing the best packaging strategy, identifying and resolving thermal management problems, developing the best method for preventing sea water intrusion, and performing pressure testing of the final design.

*Manufacturing* Set up a suitable production environment for the first prototypes. Develop quality control procedures. Develop practical procedures, tools, and fixtures. Establish storage and handling procedures for components and the finished product

## APPROACH

Our approach to the development of these batteries can be best understood in the context of the final product, shown below:



***Figure 1: Batteries with charging computer. The cell stacks are encapsulated, while the intelligent controller sits in an oil filled cavity at one end. This cavity has an aluminum lid with external wires through liquid tight fittings.***

***Table 1: Electrical, chemical and physical characteristics***

<b>Model</b>	1020	2040	3500
<b>Capacity</b>	1020Wh	2040Wh	3500Wh
<b>Cells</b>	Lithium Polymer		
<b>Voltage</b>	30V nominal (32V to 26V over full discharge)		
<b>Nominal Capacity (C)</b>	35Ah	70Ah	118Ah
<b>Max. Discharge rate</b>	17A	30A	30A
<b>Max Charge Rate</b>	10A	20A	25A
<b>Expected cycle life</b>	85% capacity after 500 cycles		
<b>Shelf life</b>	Indefinite, but will self discharge in 6-12 months		
<b>Length x Height x Width</b>	11"x10.5"x5"	18.3"x10.5"x5"	28.6"x10.5"x5"
<b>Mass</b>	15kg	27kg	42kg

Our technical approach evolved under the pressures of an aggressive field deployment schedule. Early on in the program the new batteries were needed for our AUV developments, and we deployed several prototypes in vehicles. They certainly had their problems, but the urgency and practical experience brought to the program were invaluable. Another programmatic decision was to decouple mechanical and electrical development tracks, by not making the intelligent battery controller board integral to the cell stacks. This allowed us to make independent advances in the two areas at a fast pace.

*Electrical* The internal wiring for batteries that are being built for Bluefin AUV's provides a voltage of 30V, but halving or doubling the voltage is simple as far as the wiring is concerned. The size of the cell stacks meet different capacity requirements: 1, 2, and 3.5kWh. The batteries' internal wiring provides ample current carrying capacity for the main power, access to individual brick voltages and 4 internal temperature sensors. The wiring has been designed such that a minimum of mechanical stress is imparted to the cells during assembly and service.

The wet wiring comes through the lid on the battery cavity through liquid-tight fittings. It consists of two molded pig-tails with wet-mateable connectors, one positive and one ground. The ground cable also has wires for serial communication, and the enable function, described below. Keeping the positive and negative conductors separate reduces the chance of a catastrophic short caused by sea water intrusion in the external wires.

*Intelligence* The batteries' integral electronics package protects the pack from out-of-specification conditions, monitors and logs charge and discharge, performs balancing of cells, switches the battery on or off, and communicates status information to vehicle or shore computers. The current design has cell balancing capability, as well as extra electronic protection of the pack external to the board firmware. The monitoring electronics are also responsible for measuring voltages and current through the pack as well as total pack voltage.

One of the penetrators includes an enable wire. When this wire is grounded, the board powers up and enable the battery. The inclusion of the Power Switching components and protection diodes in the Battery Packs permits in-situ charging, through a shore cable.

The battery controller has watch dog functionality. The board expects a valid communication from the Main Vehicle Computer or charge computer within a certain time. If no communication is received

then the board will shut down all power outputs but remain communicative. Communications are half duplex RS485, and all boards have a unique 2-digit address, allowing several battery packs to be multiplexed onto a single serial channel.

*Automated Charging* The charging station provides the interface to the battery for charging and conditioning. It makes full use of the capabilities of the intelligent controller to monitor and control the battery and, as well as controlling the power supply, all of which takes place via a unified graphical user interface.

*Mechanical* The prototype batteries that we first produced consisted of bricks of cells that were encapsulated individually then put in oil filled enclosures together with the electronics. The enclosures were off-the-shelf die cast aluminum boxes, modified for corrosion protection and electrical feed-troughs. This approach allowed us to deploy pressure tolerant prototype batteries at a very early stage of the project. Since maintaining such a large pressure-balanced, oil-filled volume is impractical from a logistics, packaging, cost, and energy density perspective, we started developing methods for encapsulating the cell stacks.

The next design was a completely cast battery, without electronics. It was rather simple in construction, and worked well for several dives, but some would then suffer a failure. We believe this was most likely due either to water intrusion through paths in the encapsulation, or mechanical stress and shorting in the internal wiring.

Our current design draws on all the previous experience. The cell assembly is completely encapsulated, with an oil filled electronics cavity molded directly in. The requirements for the encapsulation process of the batteries were: (a) withstand repeated submergence in sea water, without electrical or mechanical failure. (we expect 500 or more deployments, up to 20 hours at a time); (b) withstand 7000 psi hydrostatic pressure during service, without straining any part of the battery internals; (c) withstand lifting and normal handling in the field associated with removal from vehicle for charging or transport; (d) not be detrimentally affected by oil, sea water, air, or daylight; and (e) not cause damage to cells by shorting during manufacture.

This production process has numerous advantages:

- High degree of water ingress protection
- Length of battery grows according to energy requirement
- Space and weight efficient
- No cable exits in cast – cables are replaceable
- Operationally efficient – small oil volume
- Upgrade and repair of electronics and wiring possible
- Decouples electronic and mechanical design process
- Replaceable fuses can be employed

There are of course some drawbacks to this approach, and have taken steps to minimize their impact.

- Individual cell bricks are not replaceable – extensive testing during manufacture necessary to ensure quality
- Single water intrusion barrier – encapsulation must be top notch

#### *Personnel (FY2002)*

Dr Richard Wilson, Michael Allen, Richard Hillis: Electrical engineering, Intelligence

Dr Knut Streitlien, Einar Gustafson, Josh Eck: Mechanical design and assembly

Alex Bednarzh, Beth Bauman, Mark Derome: Manufacturing, Charging

Bluefin Technical Management Team: Design input

Bluefin Operations Group: Pressure testing, field service, operational design feedback

### **WORK COMPLETED**

We performed the steps outlined above to develop a viable production prototype. We then set out to streamline the manufacturing process, improving the product quality, logistics and planning, automating quality control, training personnel, and developing better tools and fixtures. Since then we have completed production and delivery of over 50 batteries of all sizes. They are now the standard energy source for our AUVs, and several have been delivered to outside customers. The batteries have been successfully pressure tested to 4950m.

### **RESULTS**

We have shown that a practical battery for deep ocean service can be produced without resorting to one-atmosphere or oil-filled housings. Taking the technical risk of encapsulating large stacks of cells in solid material has paid off and resulted in batteries with unparalleled performance and operational envelope. Extensive field deployment resulted in hardened components, design specifications reflecting real world conditions, and rapid adoption of the technology. We demonstrated that the sophisticated electronics required for controlling the battery can be incorporated in a very compact, yet serviceable package. By using state of the art rechargeable cells that are driven towards improved performance by consumer market demand, these batteries are poised to get even better and less expensive in the years ahead.

### **IMPACT/APPLICATIONS**

Most underwater systems and instruments will benefit from this development, yielding significant increases in range and endurance, while reducing cost and service requirements. These batteries will power AUVs in scientific and military applications, as well as the critical off-shore oil and sub-sea telecommunications industries. Our market study shows that, by 2005, AUV applications alone will constitute a multi-million dollar market for these batteries. In addition, the prospects for non-AUV uses are at least as promising. These include self powered ROVs or hybrid ROV/AUVs, navy and science manned submersibles, stationary installations for naval, scientific, and commercial applications, and even non-submersible applications where rugged, smart, high energy density power sources are required.

## **TRANSITIONS**

Bluefin's pressure-tolerant batteries have recently been installed and successfully demonstrate in the Battlespace Preparation AUV (BPAUV). During Fleet Battle Experiment- J, these batteries allowed the BPAUV to set a new endurance record with the completion of a 17 hour wide-area MCM survey mission. The pressure-tolerant batteries are also now a commercial product, available to customers in the above mentioned fields. In total, over 100 kW-hr have been sold to scientific, commercial and military customers.

## **RELATED PROJECTS**

- AO/FNC
- US/UK
- BPAUV
- US/UK Follow on